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# Electroweak Condensates at Standard Top Mass Values *

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**Abstract**

In the two Higgs-doublet SM, perturbativity breaks down below $\Lambda_{Planck}$: For $m_{top} = 170 - 180$ GeV, $g_{top}$ reaches the pole at scales below 1000 TeV if the ratio of VEV's $v_u/v_d$ is smaller than 1. We discuss top condensate scenarios assuming 150 GeV $\leq m_{top} \leq$ 200 GeV: The phenomenological work of the last years shows a version with two composite Higgs doublets as a viable option. In the theoretical frame of gauge extensions, a second doublet does not come with additional parameters, but is dictated by the symmetry.

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Top condensate models have been motivated a few years ago when the top mass $m_{top} = \frac{1}{\sqrt{2}} g_{top} v$ became known to be as heavy as 60 or 70 GeV [1]. With such masses, top is the only elementary fermion with $m_{top}/M_W = \mathcal{O}(1)$ and this - rather than the fact that the top is heavier than all remaining eleven fermions together - is what makes the top quark special: the dynamics of $m_{top}$ and $M_W$ must be related. The minimal, effective model replaces the standard Higgs-sector by an NJL interaction involving $t$ and $b_L$,

$$G \bar{\Psi}^i_L t_{iR} \bar{t}^j_R \Psi_{jL}, \qquad \Psi = \begin{pmatrix} t \\ b \end{pmatrix}, \qquad i,j = 1, ...N, \tag{1}$$

which gives rise to a composite $\sigma$-model if $G > G_c = 8\pi^2/N$. The scalar states are a massive $\bar{t}t$ and massless $\bar{t}\gamma_5 t$, $\bar{b}_L t_R$, $\bar{t}_L b_R$. The top has no bare mass term and achieves a dynamical one via a self-consistent Schwinger-Dyson summation.

Because we now have growing evidence for $m_{top} \simeq 174$ GeV from CDF [9], it is useful to take a fresh look on this well motivated kind of model under the assumption

$$150 \text{ } GeV < m_{top} < 200 \text{ } GeV. \tag{2}$$

It will be useful to follow the discussion of the model like it proceeded in the major part of the literature within the last 5 years, because the model variations left first statements mainly intact and numerical changes of predictions can be derived directly from the extension or variation under consideration. The result will be that all such numerical changes are small for viable parameter ranges, i.e. the prediction of the minimal model is (maybe surprisingly) stable in extensions. What has often been regarded as a failure to construct models with the correct $m_{top}$ prediction now turns out to be a confirmation of the two composite Higgs-doublet case: Models with one Higgs-doublet predict $m_{top} > 200 GeV$, while a two Higgs-doublet model predicts $m_{top}$ in the range (2) with a condensation scale possibly as low as a few TeV.

The pure NJL prediction is given by the relation $m_H = 2m_{top}$, but $SU(3)_c \times SU(2)_L \times U(1)$ gauge interactions must be included. They have been accounted for in solving the SM RG-equation for $g_{top}$ with the boundary condition $g_{top}(\mu \to \Lambda_c) \to \infty$, where $\Lambda_c$ is the condensation scale at which the composite scalar field $\bar{t}t = Z(\mu)\phi_0$ vanishes with $Z = g^0_{top}/g_{top}$ [2]. This is practically the same as considering the running of $g_{top}$ in the minimal SM itself and looking for the Landau pole. The use of 1-loop RG-equations in

this procedure is believed to be a meaningful approximation, because the breakdown of perturbativity takes place not too far below $\Lambda_{Planck}$ [10] and numerical calculations support the results [3]. It is well-known that in the minimal model, $m_{top}$ comes out too large: values are above the window allowed by the $\rho$-parameter even for very highly tuned $\Lambda_c > 10^{16}$ GeV. This is saying that the pole is not reached before $\Lambda_{Planck}$ if $m_{top} < 200$ GeV. Thus we are confronted with an extreme (and in fact a worse case) of the unnatural Standard desert situation, as all quadratic divergencies have only been absorbed into the top mass counterterm.

The situation drastically changes, if the scalar sector possesses two doublets: the VEV's of up- and down-type Yukawa couplings add up in the $W$ self-energy and therefore have to satisfy $v^2 = v_u^2 + v_d^2$. This simply causes a lower $v$ to enter the fermion mass $\frac{1}{\sqrt{2}} g_f v$ so that $g_f$ has to be fitted to a higher value. The influence can be read off best from table 1 by Kim and Cvetic [10]. For values (2) the breakdown is then reached at comfortable scales 1-1000 TeV, if $v_u/v_d < 1$. Such ratios enhance the running of $g_{top}$. The same was found in the supersymmetric version of the TMSM [17], where the second doublet and quadratic divergencies appear in a different context.

The second serious objection against the minimal TMSM, put forward mainly by A. Hasenfratz et al., concerned predictability [6]: The pure effective NJL terms induce all sorts of higher dimensional counterterms. Among them are derivative couplings, which correspond to momentum dependent loop diagrams like Fig.1, [5]. These terms represent the propagation of the bound state (the internal loop) and inclusion of the complete series of derivative couplings, each with a free coefficient, leads back to the SM universality class. Having this critics only qualitatively in mind, gauge interactions were used to yield the NJL operator on the Fermi scale as a well-defined part of a complete gauge boson exchange: The new parameters are a gauge coupling $g_{new}$, a degree of freedom $N$ to expand in and a new scale $\Lambda_c \ll \Lambda_{Planck}$, all of which have definite physical meaning, such that we now gain information on physics beyond the SM out of the composite Yukawa sector [8]. Higher dimensional terms are calculable and small for viable ranges of $\Lambda_c$ (second ref. [4]).

The gauge extension causes deviations from the pure NJL prediction and we want to classify the new effects in a model-independent way as far as possible. The new boson(s) shall be strongly coupled and heavy. It is useful to expand the new interaction in powers of $p^2/M^2$, where $M \sim \Lambda_c$ is the new

mass and $p$ a typical momentum and write the complete form as:

$$\mathcal{L} = J_L^2 + J_R^2 + J_L J_R + J_R J_L + \mathcal{O}(p^2/M^2), \tag{3}$$

$$J_L J_R + J_R J_L = \sum_{i,j=1}^{N} \frac{G_{LR}}{M^2} \left(\bar{\psi}_L^i \psi_{iR}\right) \left(\bar{\psi}_R^j \psi_{jL}\right) + h.c. \tag{4}$$

$$\begin{aligned} J_L^2 &= \sum_{i,j=1}^{N} \frac{G_{LL}}{M^2} \left(\bar{\psi}_L^i \gamma^\mu \psi_{iL}\right) \left(\bar{\psi}_L^j \gamma_\mu \psi_{jL}\right), \\ J_R^2 &= \sum_{i,j=1}^{N} \frac{G_{RR}}{M^2} \left(\bar{\psi}_R^i \gamma^\mu \psi_{iR}\right) \left(\bar{\psi}_R^j \gamma_\mu \psi_{jR}\right), \end{aligned} \tag{5}$$

Here we can see that the model is not in one universality class with the SM: $J^2_{L(R)}$ and $\mathcal{O}(p^2/M^2)$ are new terms which cannot be decoupled from weak physics, because tuning the new physics to scales $\Lambda_c \gg M_W$ must keep $M_W$ itself fixed. This can only be done by simultaneously tuning $G_{LR} \to G_c$ and this takes place in every channel of eq. (3) as $G_{LR} \sim G_{LL(RR)}$. Additional predictions from these additional operators will remain at low energies and there is no way to reach the minimal SM as a limit. Let us now recall the known results from those non-minimal predictions/effects, beginning with $\rho$:

The Fierz-eigenstates $J_L^2$ and $J_R^2$ contribute to the bubble summation which corrects $\rho$, Fig. 2. They have been calculated to $\mathcal{O}(1/N)$ for $p^2 = 0$ and found to be negligible [11].

The next important part that contributes to $\rho$ is the vector resonance spectrum. It is of course completely model-dependent and constitutes the yet unknown part of new effects in $\rho$. Vector resonances will show non-decoupling as discussed above. On the other hand, one expects these resonances to be uncritical, i.e. although the tuning enters in the corresponding channel, divergencies remain as no gap-equation automatically removes them. Therefore they shall be of $\mathcal{O}(\Lambda_c)$ and the decoupling takes place for this mass to suppress the influence on observables at low energies (like especially $\rho(0)$).

Using a dynamical function $\Sigma_{top}(p^2)$ in the $W$-self-energy, A. Blumhofer and M. Lindner argued that a cancelation of the SM $m_{top}^2$ term in $\rho$ can take place if $\Sigma_{top}$ has some kind of resonant enhancement at $\sim 5m_{top}$ [12].

A further effect comes from $\mathcal{O}(p^2/M^2)$ terms in eq.(3). They represent the $p$-dependent short distance parts of the propagator of new bosons and thus

easily cause additional resonances (radial excitations of composite states). M. Lindner and D. Lüst have considered additional scalars and vectors in the SM-RG-eq. [13]. The running of $g_{top}$ is altered by a change of slope at the scale of the resonance. Additional scalars (vectors) result in a decreasing (increasing) $m_{top}$ and one additional scalar at 100 GeV in the otherwise minimal SM for example allows $m_{top} < 200$ GeV at $\Lambda_c \sim 10^{11}$ GeV. Altogether, the $\mathcal{O}(p^2/M^2)$ terms do not drastically change predictions if not a number of scalars form around $M_W$. This requires $M$ to be of $\mathcal{O}(M_W)$, a too low value.

In all these examples above non-standard effects are sizeable only if $M(\sim \Lambda_c) \lesssim 1$ TeV. The analysis of non-standard $p_T$ in $\bar{t}t$ production has not been shown to give a different result [14]. We should now look for lower bounds on $M$.

A $Z'$ mass is of course limited already in precision measurements. Perturbative bosons are usually bounded to be heavier than a few hundred GeV, depending on the details of the model which give the physical couplings of the various precisely measured channel [15]. For a strongly coupled $Z'$, the limit depends on the effective fermionic coupling $g_{new}^2 = G$ of $Z'$, which has to exceed the critical coupling $8\pi^2/N$. The limit thus depends on $N$. A strong coupling at LEP100, assuming $N = 3$, gives a typical limit $M_{Z'} > 3$ TeV [16], Fig. 3. If no new bosons are found at LEP200 or a 500 GeV $e^+e^-$ collider, the limit increases to 15 TeV and 50 TeV respectively, Fig. 4. This analysis uses a static coupling and correct running of $g_{new}$ in the critical channels can cause drastic changes, non-critical channels will however remain to be strong at low energies.

Collecting the above points, we see that i) augmenting the interaction eq.(1) to eq.(3) does not significantly effect the result of the pure NJL gap-equation or standard RG-running unless $\Lambda_c \lesssim 1$ TeV and ii) such scales seem rather unlikely from experiment already. Turning this around, the NJL-RG prediction is rather stable to hold in a gauge extension at an expected

$$\Lambda_c \gtrsim 1 \text{ TeV}. \tag{6}$$

This disfavors the one Higgs-doublet model under the assumption (2), while the two doublet model can live well with (2) and (6): A lack of non-standard negative contributions to low energy observables like $\rho$ in this scenarios preserves indirect measurements of $m_{top}$ to contradict with the NJL-RG result (table 1).

Let us make a remark on a previously proposed type of model. The empirical scaling formula for masses $m_i$ across flavor components $i = 1, 2, 3$, $m_2/m_1 = 3\,(m_3/m_2)^{\frac{3}{2}|Q|}$, [18], tells us that $Q$ can be used for the mass splitting. The most straightforward way to involve $Q$ in the top condensate model is to couple the new boson to hypercharge currents by mixing in $SU(2)_R$ or any other hidden factor of the SM [7, 8]. The scalar couplings $G_{LR}$, relevant in the SD-eq., are proportional to

$$Y_L \cdot Q = \begin{cases} \frac{1}{6}\cdot\frac{2}{3} & \text{for } I_{W_3} = 1/2 \text{ quarks,} \\ \frac{1}{6}\cdot(-\frac{1}{3}) & \text{for } I_{W_3} = -1/2 \text{ quarks.} \end{cases} \tag{7}$$

The mass matrix is of rank 1 in generation space. According to eq. (7) only $I = +1/2$ quarks condense, while the interaction is repulsive for $I = -1/2$ quarks, i.e. interaction eq. (1) is recovered and only the top is massive. There is an analogous term for the leptons, $\bar{\Psi}_L \tau_R \bar{\tau}_R \Psi_L,\ \Psi = (\nu_\tau, \tau)^T$, which among leptons produces only a mass for the $\tau$. This channel is stronger than the top-bottom system, $Y_L \cdot Q = -\frac{1}{2}\cdot(-1)$, for $I_{W_3} = -1/2$ leptons, possibly leading to the required situation $v_u/v_d < 1$. Additionally, there is one more attractive channel involving $b_R$ and $(\nu_\tau, \tau)_L$, intermediate in strength and giving rise to a system of coupled gap-equations, which has not been considered yet. A generalization of the representation was introduced in [19].

We note that there is further work on condensate type models, both without the derivation of new interactions [20] or scenarios like the inclusion of a 4th family [21] and other variations, which do not fall into special classes of models (see [4] and further refs. therein).

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